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# Electron holes in the auroral upward current region

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[1] Evidence is given for electron holes in the upward current auroral kilometric radiation (AKR) source region. Isolated parallel electric field structures of tripolar polarity are seen in FAST recordings, being interpreted in terms of trains of nested ion and electron holes such as shown in numerical simulations by Goldman et al. (2003). They are created by beam plasma interaction via the kinetic two-stream instability upstream of a strong double layer, giving rise to broadband emission spectra below the ion plasma frequency. Field amplitudes reach  $\sim 1 \text{ V m}^{-1}$  peak-to-peak and appear to modulate both the particle energy fluxes. The presence of electron holes is responsible for the fine structure of AKR emissions. **Citation:** Pottelette, R., and R. A. Treumann (2005), Electron holes in the auroral upward current region, *Geophys. Res. Lett.*, 32, L12104, doi:10.1029/2005GL022547.

## 1. Introduction

[2] High-resolution FAST observations in the mid-altitude auroral magnetosphere [Carlson et al., 1998; Ergun et al., 1998a, 1998b] have confirmed the presence of electron holes in the downward current region. Evidence for them to exist has also been accumulated in many regions preferentially where magnetic field-aligned currents are expected to flow. In the plasma sheet boundary layer [Matsumoto et al., 1994; Omura et al., 1999], at the magnetopause [Cattell et al., 2002], the bow shock ramp [Bale et al., 2002], and even in the magnetosheath [Pickett et al., 2003], though they might not always be of same nature. The importance of these holes in connection with plasma acceleration in the auroral downward current region has been stressed by numerical simulations and comparison with observation [Goldman et al., 1999, 2000; Newman et al., 2001, 2002; Oppenheim et al., 2001; Singh, 2000], and as well for reconnection solely from numerical simulation [Drake et al., 2003]. In contrast, in the upward current ‘inverted-V’ region electron holes have so far been reported only once [McFadden et al., 1999] in passing. This is surprising as the typical signatures of the upward current region are the fast downward electron beam (ring/shell distribution), and the cold upward ion beam, representing a typical two-stream configuration. Close inspection of the auroral kilometric radiation (AKR) spectrum reveals that it consists of a large number of narrow band “elementary radiation sources” (ERS) [Pottelette et al., 2001] moving along the magnetic field. The size of these sources is of the order of that expected for electron holes. In the following based on FAST

observations we present evidence for electron holes in the upward current region.

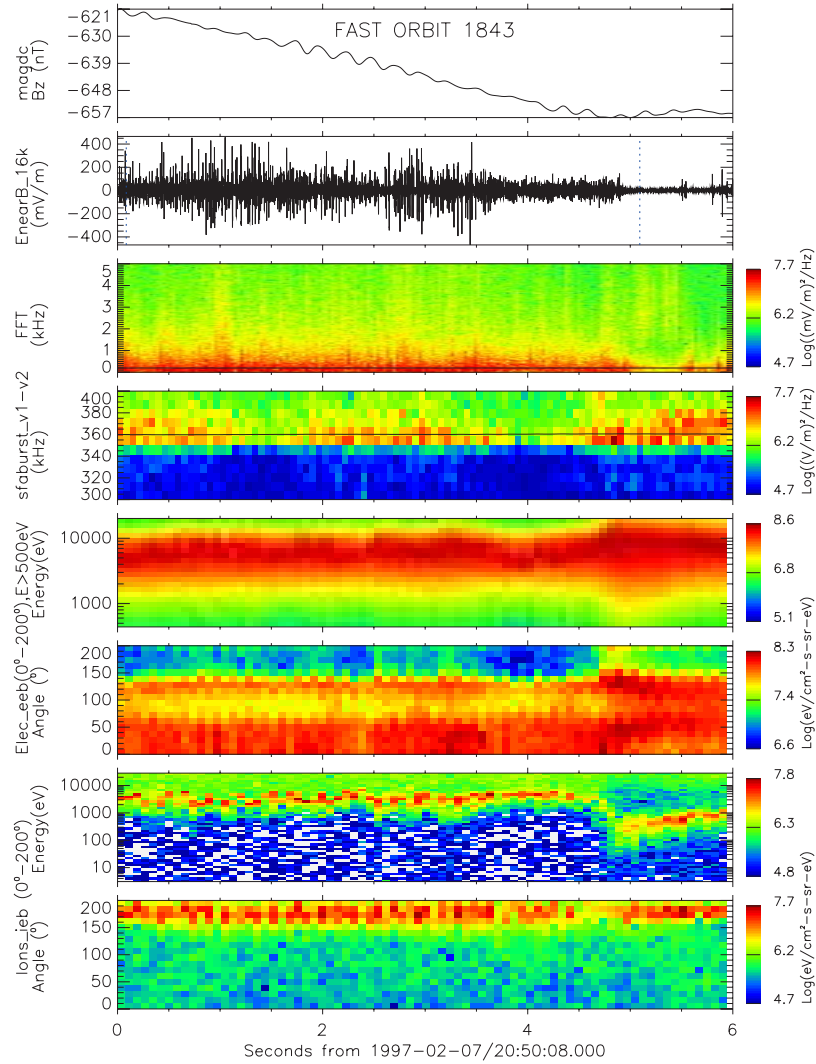
## 2. Observations

[3] The 6 s sequence of FAST particle and wave observations on 7 February 1997 at  $\sim 2300$  MLT (orbit 1843) forming the basis of our discussion is shown in Figure 1. FAST was on a poleward pass at invariant latitude  $\sim 66^\circ$  and altitude 3950 km. Panel *a* shows it crossing the upward current region (negative magnetic field gradient). Electron energy flux and pitch angle distributions are given in panels *e* and *f*, respectively. The electrons form a downward beam, broadened toward larger pitch angles but with empty loss cone, typical for the presence of a parallel electric potential drop. The energy maximum of the beam (dark line) is around 8 keV. At the same time the entire ionospheric ion population (panel *g*) in the vicinity of the spacecraft is accelerated upward ( $180^\circ$  in panel *h*) forming a cold ion beam. Panels *c* and *d* represent the low and high frequency wave activities, respectively. The presence of intense auroral kilometric radiation (AKR) generated near the electron gyro-frequency  $f_{ce}$  (black line at  $\sim 360$  kHz in *d*) indicates that the spacecraft is in the auroral acceleration region. The (AC-coupled with high pass filter above a few Hertz) 32 kHz waveform of the parallel electric component (panel *b*) exhibits a number of large-amplitude spiky emissions with amplitudes exceeding  $\sim 400 \text{ mV m}^{-1}$ . These spikes are related to broadband spectral intensifications typical for small scale structures passing the spacecraft. These spikes are correlated with increases in the central energy of the auroral electron beam (panels *c* and *e, f*). Similar changes in ion energy in relation to these intensifications (panel *g*) are expected in interaction with local parallel fields. Figure 2 shows a 200 ms snapshot of the waveform component quasi-parallel to the magnetic field around 2050:11.250 UT (called ‘E near B’ because the magnetic field is within a few degrees of the spin plane [Ergun et al., 1998b]). At this time, the spacecraft was located upstream of the accelerating layer as indicated by the  $\sim 4$  keV upward ion beam. Six large-amplitude localized isolated electric field structures of  $\leq 10$  ms duration are seen, separated by gaps of  $\sim 20$  ms filled with small-amplitude short-scale fluctuations. This quasi-regular arrangement and the large amplitudes of the structures, ranging from  $250 \text{ mV m}^{-1}$  up to  $500 \text{ mV m}^{-1}$  indicate passage of a quasi-periodic, quasi-regular chain of isolated electric field structures over the spacecraft along the magnetic field.

[4] Figure 2 (bottom) shows the power spectrum of the entire sequence. This spectrum is broadband, typical for moving spatially localized wave pulses. It extends over two decades from 100 Hz up to the plasma frequency and has power law shape of slope  $-2.2$ . The spectral maximum is at  $\sim 150$  Hz, just below the ion cyclotron frequency  $f_{ci} \approx$

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**Figure 1.** The 6 s high resolution overview of the FAST auroral magnetosphere passage in the inverted-V anti-earthward current region described in the text.

195 Hz. Electrostatic ion-cyclotron waves do not exist at these frequencies; when oblique they contribute at above  $f_{ci}$  where they are visible as modulations of the power law. Above 1 kHz the spectrum peaks at the electron plasma frequency which can be identified with the spectral maximum around  $\sim 8-9$  kHz. This value of  $f_{pe}$  agrees with the one measured by the electrostatic analyzers aboard FAST. Below and at  $f_{pe}$  the high level of fluctuations indicates the unrest and varying thermal spread of the participating electron populations. From second 4.5 to 5 the 32 kHz sampled AC-coupled parallel electric fluctuations stay at a low level. The parallel energy of the ions drops from 4 keV to 200 eV, while the parallel energy of the electrons increases continuously from 4 keV to 8 keV. This fact provides strong support for crossing a localized potential ramp of  $\sim 4$  keV amplitude parallel to the magnetic field [Pottelette *et al.*, 2004].

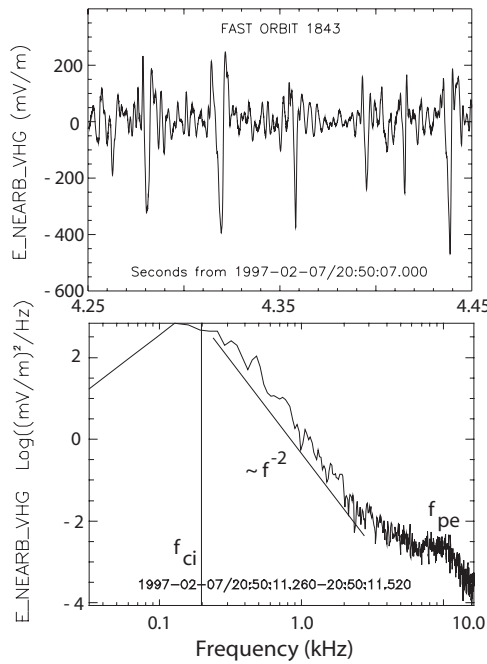
### 3. Discussion and Conclusions

[5] The above observations are in agreement with the spacecraft being close to an accelerating double layer.

Double layers in the upward current region have been observed previously by Ergun *et al.* [2003a, 2003b]. Figure 3 in its lower part shows FAST approaching and passing a negative unipolar parallel electric field ramp in the fluctuations sampled at  $\sim 512$  Hz of the DC-coupled electric field. The parallel field assumes values larger than  $1 \text{ V m}^{-1}$  in anti-earthward direction for roughly 0.5 s, being capable of accelerating electrons down and ions upward as observed. The simultaneously measured large perpendicular field corresponds to a  $<2$  Hz distortion of too low frequency for an ion-cyclotron disturbance; together with the localization of the ramp it might rather be suggestive of an inertial kinetic Alfvén pulse.

[6] We note that the spacecraft approaches the double layer from the high potential side. This layer should move upward across the spacecraft at an approximate speed of  $\sim 8 \text{ km s}^{-1}$  with respect to the spacecraft. This corresponds to a potential drop of  $\sim 4$  kV, in rough agreement with the observation of the changes in electron and ion energy.

[7] On the low potential (downstream) side of the ramp the electric field is quiet. The high potential (upstream) side exhibits very large amplitude electric field turbulence. The



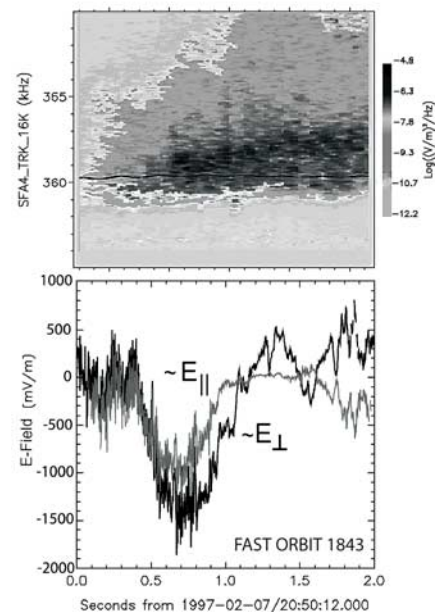
**Figure 2.** *Top:* High time resolution of 200 ms quasi-parallel electric VLF waveform showing a chain of equally spaced tripolar electric field structures embedded into a fluctuating background field. One distinguishes the deep anti-earthward field signatures flanked by two weaker earthward fields. *Bottom:* The VLF spectrum for the same time period is maximum below the cyclotron frequency and exhibits a power law shape to higher frequencies, typical for broadband noise. A second maximum is at the plasma frequency.

isolated electric field structures are located here. In contrast to the commonly observed solitary dipolar field profiles they exhibit “tripolar” electric field profiles (Figure 2) first noted by *Mangeney et al.* [1999] in the solar wind [see also *Pickett et al.*, 2004]. The anti-earthward (negative) field in their centers is flanked by two weaker-field earthward (positive) peaks, in agreement with the tripolar structures moving upward.

[8] An asymmetry between the two sides of the double layer in the observed electric field fluctuations is regularly seen in numerical simulations [*Singh*, 2000; *Newman et al.*, 2002; *Goldman et al.*, 2000, 2003]. *Goldman et al.* [2003] found that in the early state on the low potential side of the double layer the two stream instability generates fast moving electron holes. These are not seen in the observations since the early state of the evolution is missed. On the other hand, on the high potential side chains of coupled ion and electron holes evolve which move at much lower velocity of the order of the ion drift speed. Such chains may be interpreted as the tripolar structures seen in the observations. Their signatures are alternating earthward and anti-earthward electric fields. In the beam plasma system they are excited by a kinetic two-stream instability upstream of the strong microscopic double layer of several Debye length ramp extension. Previous observations in the upward current region [*Ergun et al.*, 2003b] only refer to the presence of bipolar ion holes. In the present case the tripolar

structures appear mainly excited in the immediate vicinity of the double layer with largest amplitudes, while bipolar structures become prominent only larger away.

[9] The alternating potential maxima and minima related to the tripolar train of ion and electron holes are capable of trapping and reflecting low energy electrons and ions, respectively. The simulations of *Goldman et al.* [2003] suggest that close to the double layer on the high potential side two different instabilities cooperate. One is an ion-acoustic like kinetic instability [*Kindel and Kennel*, 1971] driven by the fast ion beam at speed larger than the ion-acoustic velocity,  $v_{bi} > c_{ia}$ . It generates ion holes which reflect electrons into a reflected beam fast enough to create electron holes by the electron-ion two-stream (kinetic Buneman) instability. Since the electron temperature cannot be neglected the instability is of kinetic nature. Its most unstable frequency is close to the ion plasma frequency  $f_{pi}$ , the spectral maximum in Figure 2 at the time when the tripolar structures appear. We have  $f_{pi} \approx 150$  Hz, corresponding to a ratio  $f_{pe}/f_{pi} \approx 60$ , yielding an effective ion mass  $m_{i,eff} \approx 1.96m_p$  (with  $m_p$  the proton mass). The two main ion constituents are oxygen and protons. The effective ion mass corresponds to 52% oxygen and 48% hydrogen in reasonable agreement with the assumption on the constitution of the upper ionospheric plasma. Unfortu-



**Figure 3.** *Top:* Very high time resolution dynamical source region spectrum of AKR. The emission is partially local as indicated by the frequency being below the electron cyclotron frequency (black line). The fine structure of AKR suggests that it consists of many small-scale elementary radiators. *Bottom:* DC electric field measurement during the same time interval in parallel (gray) and perpendicular (black) directions. The parallel field exhibits a unipolar anti-earthward field typical for a potential ramp (double layer).



nately, no ion composition measurements were available during this orbit to confirm this value.

[10] The measured parallel electron temperature of  $k_B T_e \approx 1$  keV and effective mass yield an ion acoustic phase velocity  $c_{ia} \approx 200$  km s<sup>-1</sup>. For frequencies close to  $f_{pi}$ , the excited ion holes moving parallel to the auroral electron beam have velocities substantially smaller than  $c_{ia}$ . The accelerated ionospheric ion beam moves in opposite direction with an estimated velocity  $v_{ib} \approx 250$  km s<sup>-1</sup>, larger than  $c_{ia}$ . In this case the holes will propagate upward at speed  $v_h \approx v_{ib} - c_{ia}$  of several 10 km s<sup>-1</sup>. In the more general case the ion holes either propagate upward or downward depending on their velocity being smaller or larger than the ion beam speed. Since the ion acoustic dispersion curve flattens out near  $f_{pi}$ , the holes will preferably be convected upward.

[11] Elsewhere [Pottelette et al., 2001] we argued that electron holes act as ‘elementary radiation sources’ (ERS) responsible for drifting fine structure in the AKR spectrum. AKR is generated by the relativistic electron cyclotron resonance. It thus responds to phase space perturbations like electron holes that affect the electron distribution. On the other hand it is insensitive to the ion distribution and in particular to ion holes.

[12] Figure 3 (top) displays a 2 s sequence of high-time resolution AKR recorded by the Plasma Waves Tracker experiment when the satellite intersected the accelerating layer. The satellite is crossing the AKR source region as suggested by the most intense radiation being emitted at and below the local electron cyclotron frequency (black line around 360.5 kHz). The radiation consists of a large number of ERS radiating at 200–400 Hz bandwidths and drifting in frequency at a rate which ranges from 4 to 10 kHz s<sup>-1</sup>. Such bandwidths correspond to field-aligned extensions of the ERS between 1–2 km, several times the Debye length,  $\lambda_D \approx 200$  m, as suggested for the size of the electron holes. In the present case, all the observed ERS move towards lower frequency across the AKR spectrogram in agreement with the hypothesis that they are generated by slow electron holes moving up along the field line. The observed frequency drifts correspond to parallel velocities in the range 40–100 km s<sup>-1</sup>, reasonably agreeing with the previous estimate. Since the radiation hits the spacecraft from different locations, the observed ERS will be generated by holes propagating on different field lines in the AKR source of the spacecraft environment.

[13] In short, in the upward current region electron holes are associated with slowly moving tripolar isolated electric field structures. They are restricted to the high potential side in the vicinity of the electrostatic double layer which forms in the upward current region. Apparently they are also related to the presence of and tied to ion holes.

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